How to Transform a Transformer

If the transformers in your junkbox never seem to be exactly what you need for a project, VE3ERP has a solution–wind your own–and a computer program to do all the math.

By George Murphy,* VE3ERP

Did you ever have the urge to get the exact power transformer needed for a project by rewinding an old transformer from your junk box? There are several methods of selecting a transformer to rewind for a particular application. Most of them, at least in my experience, result in my trying them all and finally using the one that blows the fewest fuses.

Recently, I had occasion to design a multi-voltage DC output power supply to replace the multitude of wall-wart DC "power supplies" cluttering up every wall outlet and power bar in a friend's entertainment and computer center. The design was no problem; it was just an enlarged version of the SUPER ACADAPT[1] I have in my hamshack, but I needed a larger transformer to run it. Rather than use my usual pragmatic FUD (Fumble Until Done) technique, I decided to do it right.

What it boils down to is this: The best way to transform a transformer is to design what you want from scratch the way engineers do, look for a transformer in your junk box with a core size close to what is needed, and transform it!

A Few Definitions

I will try to spare you one of my personal pet peeves. Often when delving into an intriguing article, I am frustrated by the author using esoteric terminology I do not understand, on the assumption I am already an expert on the subject. Thus, if you are unfamiliar with "transformerspeak," here are a couple of terms you should be aware of:

Current Density (measured in circular mils [C_M] per ampere): This defines the current carrying capacity of a conductor. The higher the current density, the more current can be carried. In a power transformer this means that for a given current, high-current-density wiring will run cooler but takes up more space and requires a larger and heavier core than low-current-density wiring. It is good practice to design for the lowest current density that will do the job. Some typical densities commonly used for small power transformers are:

500 C_M/amp—intermittent light-duty service (e.g., small appliances)

700 C_M/amp—continuous-duty commercial service (e.g., communications equipment, computers)

1000 C_M/amp—continuous heavy-duty service (e.g., industrial generators, military equipment)

Core Flux Density (measured in gauss): The number of magnetic force lines per unit area. The flux density employed depends on the application, the power rating, the core material, and the frequency. Designing for a flux density higher than

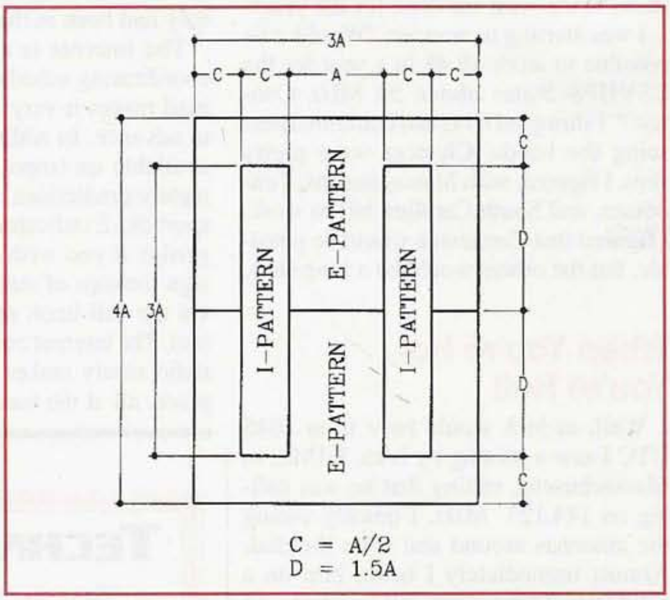

Figure 1. "EI" lamination blank for cutting transformer cores. There is no waste in this process. Figure 2 shows how the cut pieces go together.

Typical Standard Lamination Dimensions
(all dimensions in inches)

Type	Blank Size	A	C	D
75 EI	2.250 × 3.000	.750	.375	1.125
87 EI	2.625 × 3.500	.875	.4375	1.3125
125 EI	3.750 × 5.000	1.250	.625	1.875
150 EI	4.500 × 6.000	1.500	.750	2.250

Table A. The typical standard lamination dimensions.

actually required results in larger cores and heavier wires than necessary. For small transformers (up to about 50 volt-amperes, or VA) flux densities of about 14,000 gauss are commonly used.

Selecting inappropriate values of current density and core flux density may result in excessive size, inefficiency, and/or possible overheating of the transformer.

The Anatomy of a Power Transformer

The most common core form for small power transformers is the *EI* configuration, so named because the shapes of the segments resemble the letters *E* and *I*. Figure 1 shows how these segments are stamped from rectangles of sheet-iron alloy with

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no waste whatsoever. The two shapes are interleaved through a coil as shown in figures 2 and 3 to form the transformer core.

It is interesting to note how dimensions C and D are related to dimension A (C = A/2; D = 1.5A). When assembled, this forms two rectangular C wide paths for the magnetic lines of force, joined along their long sides where they become a single tongue A (2 × C) wide. Thus, it is only necessary to establish dimensions A and B to design the entire core. Once you have these dimensions, you can rummage in your junk box for a transformer with a similar-size core and carry on with the design process to determine the specifications for the new windings.

Design Philosophy

The design goal is to find the smallest possible standard core that meets your specifications with windings filling the core "windows" to maximum possible capacity. The inevitable inherent air gaps between the windings and the frame (shown exaggerated in figure 3) should be kept as small as possible. To do all this it is only necessary to decide the following:

a) Power mains voltage, and frequency in Hz.
b) Desired output voltage.
c) Desired output current in amperes.
d) Your choice of current density, in circular mils per ampere.
e) Your choice of core flux density, in gauss.

Using the Equations

If you're a math-sensitive type, you've probably noticed with fear and trepidation that this article includes 30 different equations. Fear not. I have a computer program that will do the math for you. For those who really want to understand how all this works, though, I'm going to walk you through using each of the equations.

Let's use a textbook example[2] to design a transformer with the following specifications:

a) Input 110 VAC at 60 Hz
b) Output 50 VAC
c) Output current 2 amperes
d) Current density 1000 circular mils per ampere
e) Core flux density 13,000 gauss
f) Estimated efficiency 0.90 (90%)

Plug these values into the equations shown in Table B and Table C as follows:

1) Eq. 1: Volt-Ampere Rating

$$V_A = 50 \times 2 = 100 \text{ VA}$$

2) Eq. 2: Wa Product

$$W_A = (17.26 \times 1000 \times 100) \div (60 \times 13000) = 2.2128$$

3) Eq. 3: Optimum A Dimension

$$A_{OPT} = (2.2128 \div .75)^{(1/4)} = 1.3106 \text{ inches}$$

4) From your junk box you select a transformer with the following core dimensions: A = 1.25", B = 2.0", C = 0.625", D = 1.875". You decide to use these dimensions in your calculations.

5) Eq. 4: Optimum B Dimension

$$B_{OPT} = 2.2128 \div (1.25 \times .625 \times 1.875) = 1.5106 \text{ inches}$$

6) By removing some of the laminations you will be able to reduce B to 1.500 inches, so you decide to use 1.5 inches as dimension B in your calculations.

7) Eq. 5: Input Power

$$P = 100 \div .9 = 111.11 \text{ watts}$$

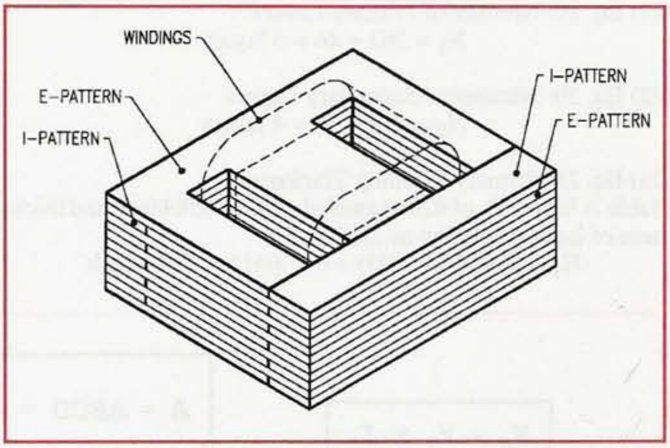

Figure 2. Transformer core stack assembly, using the "E" and "I" shaped metal pieces cut from the blanks shown in figure 1.

8) Eq. 6: Input Current

$$I_1 = 111.11 \div 110 = 1.010 \text{ amperes}$$

9) Eq. 7: Output Current

$$I_2 = 100 \div 50 = 2.000 \text{ amperes}$$

10) Eq. 8: Number of Primary Turns

$$T_1 = (110 \times 10^8) \div (28.64 \times 60 \times 1.25 \times 13{,}000 \times 1.50) = 263 \text{ turns}$$

11) Eq. 9: Number of Secondary Turns

$$T_2 = 263 \times (50 \div 110) = 119 \text{ turns}$$

12) Eq. 10: Primary Wire Diameter (circular mils)

$$A_1 = 1000 \times 1.010 = 1010\ C_M$$

13) Eq. 11: Primary Wire Diameter (inches and AWG)

$$W_1 = 31.7805 \div 1000 = .0318 \text{ inch}$$

Table A shows the nearest AWG size to be #20

14) Eq. 12: Secondary Wire Diameter (circular mils)

$$A_2 = 1000 \times 2.0 = 2000 \text{ circular mils}$$

15) Eq. 13: Secondary Wire Diameter (inches and AWG)

$$W_2 = 44.7213 \div 1000 = .0447 \text{ inch}$$

Table A shows the nearest AWG size to be #17

16) Eq. 14: Window Space Available for Coil (figure 3)

$$H = .625 - .092 - .02 = .513 \text{ inch}$$

17) Eq. 15: Width of Primary Winding (figure 3)

$$L_1 = 1.875 - (2 \times .125) = 1.625 \text{ inches}$$

18) Eq. 16: Width of Secondary Winding (figure 3)

$$L_2 = 1.875 - (2 \times .188) = 1.499 \text{ inches}$$

19) Eq. 17: Number of Primary Turns per Layer

Table A lists 28.4 turns per inch for #20 enameled wire.

$$N_{L1} = 1.625 \times 28.4 = 46 \text{ turns}$$

20) Eq. 18: Number of Secondary Turns per Layer

Table A lists 20.1 turns per inch for #17 enameled wire.

$$N_{L2} = 1.499 \times 20.1 = 30 \text{ turns}$$

21) Eq. 19: Number of Primary Layers

$N_1 = 263 \div 46 = 6$ layers

22) Eq. 20: Number of Secondary Layers

$N_2 = 119 \div 30 = 4$ layers

23) Eq. 21: Primary Winding Thickness
Table A lists O.D. of #20 enameled wire as .0364 inch and thickness of layer insulation as .005 inch.

$H_1 = 6(.0364 + .005) = 6 \times .0414 = .2484$ inch

24) Eq. 22: Secondary Winding Thickness
Table A lists O.D. of #17 enameled wire as .0506 inch and thickness of layer insulation as .01 inch.

$H_2 = 6(.0506 + .01) = 4 \times .0606 = .2424$ inch

25) Eq. 23: Total Coil Build-up (figure 3)

$H_3 = .2484 + .2424 = .4902$ inch

26) Maximum efficiency is attained when the coil completely fills space H. At this point compare H_3 (.4902 inch) with H (.513

$$V_A = V_2 \times I_2$$
Eq. 1

$$A = ABCD = \frac{17.26\, SV_A}{fG}$$
Eq. 2

$$A_{OPT} = \left[\frac{W_A}{0.75}\right]^{\left(\frac{1}{4}\right)}$$
Eq. 3

$$B_{OPT} = \frac{W_A}{0.75A^3}$$
Eq. 4

$$P = \frac{V_A}{E_{EST}}$$
Eq. 5

$$I_1 = \frac{P}{V_1}$$
Eq. 6

$$I_2 = \frac{V_A}{V_2}$$
Eq. 7

$$T_1 = \frac{V_1 \times 10^8}{28.64 fAGB}$$
Eq. 8

$$T_2 = T_1 \frac{V_2}{V_1}$$
Eq. 9

$$A_1 = SI_1$$
Eq. 10

$$W_1 = \frac{\sqrt{A_1}}{10^3}$$
Eq. 11

$$A_2 = SI_2$$
Eq. 12

$$W_2 = \frac{\sqrt{A_2}}{10^3}$$
Eq. 13

$$H = C - B_T - C_T$$
Eq. 14

$$L_1 = D - 2M_1$$
Eq. 15

$$L_2 = D - 2M_2$$
Eq. 16

$$N_{L1} = L_1 \times T_{L1}$$
Eq. 17

$$N_{L2} = L_2 \times T_{L2}$$
Eq. 18

$$N_1 = \frac{T_1}{N_{L1}}$$
Eq. 19

$$N_2 = \frac{T_2}{N_{L2}}$$
Eq. 20

$$H_1 = N_1(E_1 + P_1)$$
Eq. 21

$$H_2 = N_2(E_2 + P_2)$$
Eq. 22

$$H_3 = H_1 + H_2$$
Eq. 23

$$F_1 = T_1 \frac{2(A+B+4B_T) + \frac{2\pi H_1}{2}}{12}$$
Eq. 24

$$F_2 = T_2 \frac{2(A+B+4B_T) + \frac{2\pi(H_1+H_2)}{2}}{12}$$
Eq. 25

$$C_1 = R_1 \times I_1^2$$
Eq. 26

$$C_2 = R_2 \times I_2^2$$
Eq. 27

$$W_T = 0.27(6BA^2)$$
Eq. 28

$$C_o = 1.1(C_1 + C_2)$$
Eq. 29

$$E_{CAL} = \frac{100V_A}{V_a + C_1 + C_2 + C_o}$$
Eq. 30

Table B. Power transformer equations.

- A_1 = Primary wire diameter in C_M
- A_2 = Secondary wire diameter in C_M
- A = Tongue width (in.)
- A_{opt} = Optimum tongue width (in.)
- B_{opt} = Optimum stack height (in.)
- B_T = Bobbin allowance (.092 in.)
- B = Stack thickness (in.)
- C = Window width (in.)
- C_M = Circular mils = (wire diameter in inches × 1000)^2
- C_T = Cover allowance (.02 in.)
- C_O = Estimated core loss (ohms)
- C_1 = Pri. wire copper loss (ohms)
- C_2 = Sec. wire copper loss (ohms)
- D = Window length (in.)
- E_1 = Pri. wire enamel O.D. (Table A)
- E_2 = Sec. wire enamel O.D. (Table A)
- E_{EST} = Estimated efficiency (decimal)
- E_{CAL} = Calculated efficiency
- f = Mains frequency (Hz)
- F_1 = Length of primary wire (feet)
- F_2 = Length of secondary wire (feet)
- G = Core flux density (gauss)
- H = Available space for coil (fig. 3)
- H_1 = Primary winding thickness
- H_2 = Secondary winding thickness
- H_3 = Total coil build-up (fig. 3)
- I_1 = Input current (amps)
- I_2 = Output current (amps)
- L_1 = Width of pri. windings (fig. 3)
- L_2 = Width of sec. windings (fig. 3)
- M_1 = Margin, pri. (fig. 3 & Table A)
- M_2 = Margin, sec. (fig. 3 & Table A)
- N_1 = No. of primary layers
- N_2 = No. of secondary layers
- N_{L1} = No. of primary turns per layer
- N_{L2} = No. of secondary turns per layer
- P = Input power (watts)
- P_1 = Pri. layer insulation (Table A)
- P_2 = Sec. layer insulayion (Table A)
- R_1 = Resistance of pri. wire @ 50°C
- R_2 = Resistance of sec. wire @ 50°C
- S = Current density (C_M per amp)
- T_1 = Number of primary turns
- T_2 = Number of secondary turns
- T_{L1} = Pri. turns per inch (Table C)
- T_{L2} = Sec. turns per inch (Table C)
- V_1 = Input voltage
- V_2 = Output voltage
- VA = Volt-Ampere rating
- W_1 = Primary wire diameter (in.)
- W_2 = Secondary wire diameter (in.)
- W_A = Product of A × B × C × D
- W_T = Estimated core weight (lbs.)

Table C. Variables used in the equations.

inch) calculated by Eq. 14 in step 16 above. This indicates a clearance of about .023 inch between the coil stack and the core, which is quite acceptable.

If H_3 is greater than H, you can decrease it by reducing the wire size and/or number of turns by any, or a combination of any, of the following options:

a) Increase core lamination dimension B (reduces turns, increases weight).

b) Reduce current density (reduces wire sizes, increases temperature rise).

c) Reduce output current (reduces wire sizes, lowers VA rating).

Or, if H_3 is considerably less than H, do the opposite. In either case it will require going through the entire procedure again. For those of us with computers, there is a quick and easy way of doing the whole design from the start by using *HAMCALC*'s "Power Transformer Design" program.[3] A *HAMCALC* printout of the example we are working on is shown in figure 4.

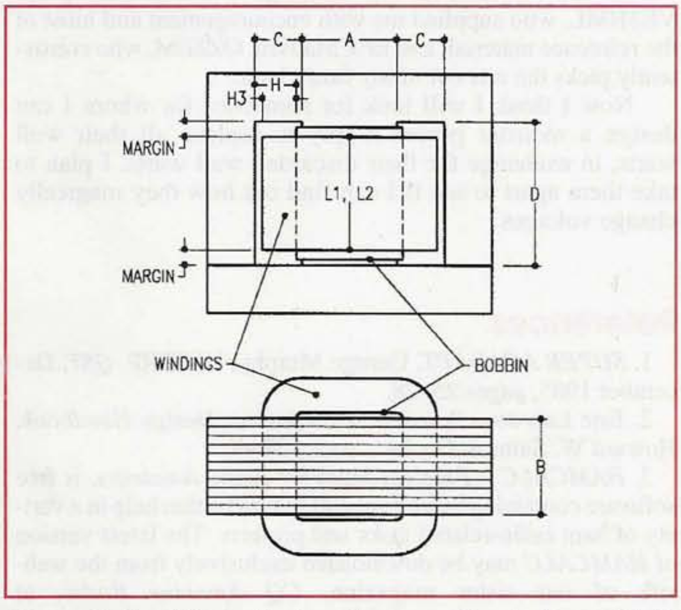

Figure 3. Final form of a transformer, with windings added. Dimension B is optimum when it is approximately equal to dimension A.

27) Eq. 24: Length of Primary Wire

$$F_1 = 263(2 \times 3.118 + [2 \times 3.141593 \times .2485 \div 2]) \div 12$$
$$= 263(6.236 + .7807) \div 12 = 153.78 \text{ feet}$$

Design for a 60 Hz, 100 VA Power Transformer

Current density	1000.0 C_M/amp
Core flux density (silicon core)	13.0 kilogauss
Selected lamination dimension A	1.250 in.
Selected lamination dimension C	0.625 in.
Selected lamination dimension D	1.875 in.
Selected lamination dimension B	1.500 in.
Input power @ 90% estimated efficiency	111.1 watts

	Primary	Secondary	
Voltage	110.000 V	50.000 V	
Number of turns	263	119	
Current	1.010 amp	2.000 amp	
Minimum wire diameter	0.032 in.	0.045 in.	
Selected wire diameter	0.032 in.	0.045 in.	
Selected wire gauge number	20 AWG	17 AWG	
Turns per layer	46	30	
Number of layers	6	4	
Length of wire	153.78 ft.	77.13 ft.	
Resistance of wire @ 50°C	1.75 Ω	0.44 Ω	
Copper loss @ 50°C	1.78 Ω	1.75 Ω	(total loss = 3.53 Ω)
Total layer thickness	0.603 in. (to fit 0.625 window dim. C)		
Approximate weight of core	3.8 lb. (estimated core loss 3.89 Ω)		
Approximate actual efficiency	93.1%		

Core Dimensions

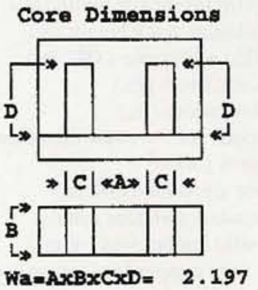

Figure 4. Power transformer design program results after plugging in the values specified in the text.

28) Eq. 25: Length of Secondary Wire

$$F_2 = 119(2 \times 3.118 + [2 \times 3.141593 \times \{.2485 + .2424\} \div 2]) \div 12$$
$$= 119(6.236 + 1.5422) \div 12 = 77.13 \text{ feet}$$

29) Eq. 26: Primary Wire Copper Loss

Table A lists resistance of #20 wire at 50°C as 13.37 ohms per 1000 feet; therefore:

$$R_1 = 153.78 \div 1000 \times 11.37 = 1.7485 \text{ ohms}$$
$$C_1 = 1.7485 \times 1.0201 = 1.78 \text{ ohms}$$

30) Eq. 27: Secondary Wire Copper Loss

Table A lists resistance of #17 wire at 50°C as 5.67 ohms per 1000 feet; therefore:

$$R_2 = 77.13 \div 1000 \times 5.67 = .4373 \text{ ohms}$$
$$C_2 = 0.4375 \times 4.0000 = 1.75 \text{ ohms}$$

31) Eq. 28: Estimated Core Weight

$$W_T = 0.27 \times 6 \times 1.5 \times 1.5625 = 3.8 \text{ lb.}$$

32) Eq. 29: Estimated Core Loss

Assuming core loss is 110% of copper loss, then

$$C_O = 1.1 \times (1.78 + 1.75) = 3.883 \text{ ohms core loss}$$

33) Eq. 30: Calculated Efficiency

$$E_{CAL} = (100 \times 100) \div (100 + 1.78 + 1.75 + 3.883)$$
$$= 10{,}000 \div 107.413 = 93.1\%$$

This completes all the nasty math.

Conclusion

Using the basic design values derived from these equations you can proceed with removing the windings from your junk-box transformer and rewinding it to suit your needs. This basic design is probably all that is needed for most amateur radio applications, and it is the starting point for further detailed design aimed primarily at reducing weight, cost, and amount of copper; increasing efficiency; and other mass-production matters so dear to the hearts of transformer manufacturers. If you want to know more about these matters, read Eric Lowdon's *Practical Transformer Design Handbook* (see footnotes). It has 16 chapters and over 250 pages devoted to them!

Much of the credit for this article goes to Curt Thompson, VE3HML, who supplied me with encouragement and most of the reference material, and Erik Madsen, OZ8EM, who consistently picks the nits out of my fuzzy logic.

Now I think I will look for someone for whom I can design a monster power supply to replace all their wall warts, in exchange for their discarded wall warts. I plan to take them apart to see if I can find out how they magically change voltages.

References

1. *SUPER ACADAPT,* George Murphy, VE3ERP, *QST,* December 1985, pages 25–28.

2. Eric Lowdon, *Practical Transformer Design Handbook,* Howard W. Sams & Co. Inc., pages 39–40.

3. *HAMCALC – Painless Math for Radio Amateurs,* is free software containing more than 200 programs that help in a variety of ham radio-related tasks and projects. The latest version of *HAMCALC* may be downloaded exclusively from the website of our sister magazine, *CQ Amateur Radio*, at <http://www.cq-amateur-radio.com>. Look for the "Download *HAMCALC*" prompt. The Power Transformer Design program is included on Version 43 or later of HAMCALC. At press time, the most current version was 66. ■